

# GRAVEL SEDIMENT ROUTING FROM WIDESPREAD, LOW-INTENSITY LANDSCAPE DISTURBANCE, CURRENT RIVER BASIN, MISSOURI

ROBERT B. JACOBSON<sup>1</sup>\* AND KAREN BOBBITT GRAN<sup>2</sup>†

<sup>1</sup>*US Geological Survey, 4200 New Haven Road, Columbia, MO 65201, USA*

<sup>2</sup>*Carleton College, Northfield, MN 55057, USA* *Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis, MN 55455, USA*

*Received 30 October 1997; Revised 20 February 1999; Accepted 23 March 1999*

## ABSTRACT

During the last 160 years, land-use changes in the Ozarks have had the potential to cause widespread, low-intensity delivery of excess amounts of gravel-sized sediment to stream channels. Previous studies have indicated that this excess gravel bedload is moving in wave-like forms through Ozarks drainage basins. The longitudinal, areal distribution of gravel bars along 160 km of the Current River, Missouri, was evaluated to determine the relative effects of valley-scale controls, tributary basin characteristics, and lagged sediment transport in creating areas of gravel accumulations. The longitudinal distribution of gravel-bar area shows a broad scale wave-like form with increases in gravel-bar area weakly associated with tributary junctions. Secondary peaks of gravel area with 1.8–4.1 km spacing (disturbance reaches) are superimposed on the broad form. Variations in valley width explain some, but not all, of the short-spacing variation in gravel-bar area. Among variables describing tributary drainage basin morphometry, present-day land use and geologic characteristics, only drainage area and road density relate even weakly to gravel-bar areal inventories. A simple, channel network-based sediment routing model shows that many of the features of the observed longitudinal gravel distribution can be replicated by uniform transport of sediment from widespread disturbances through a channel network. These results indicate that lagged sediment transport may have a dominant effect on the synoptic spatial distribution of gravel in Ozarks streams; present-day land uses are only weakly associated with present-day gravel inventories; and valley-scale characteristics have secondary controls on gravel accumulations in disturbance reaches. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: channels; deposition; erosion; fluvial; gravel-bed streams; landscape disturbance; Ozarks; Ozark Plateaus; sediment routing; sediment transport; sediment waves; sedimentation; sediment storage; rivers

## INTRODUCTION – SEDIMENT ROUTING FROM LAND-USE DISTURBANCE

One of the most complex and challenging problems in geomorphology is understanding how sediment moves through river systems (Wolman, 1977). The overall process of sediment erosion, delivery to stream channels, and episodic downstream movement is referred to as sediment routing. Once delivered to the stream channel, sediment typically does not move as rapidly or directly as the water that transports it through alluvial systems. Instead, sediment can be deposited on the channel beds, banks and bars, and remain in storage for highly variable time intervals before being remobilized and continuing its downstream travel (Meade *et al.*, 1990). Transport distance between deposition episodes and residence time in storage are highly dependent on particle-size characteristics, channel and floodplain morphology, and energy of the alluvial system.

---

\* Correspondence to: Dr R. B. Jacobson, USGS, Columbia Environmental Research Center, 4200 New Haven Road, Columbia, Missouri 65201, USA

† Present address: Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis, MN 55455, USA

Contract/grant sponsor: US Geological Survey Global Change Research Program

Contract/grant sponsor: Ozark National Scenic Riverways (National Park Service)

Contract/grant sponsor: Missouri Department of Conservation

Human-induced landscape disturbance has the potential to deliver large quantities of sediment to streams (Hooke, 1994) either from point sources – such as mining operations – or from non-point sources – such as urbanization, agriculture or timber production. In either case, assessment of downstream effects depends on understanding rates and processes of sediment routing. For non-point sediment sources, an additional consideration is how sediment derived from widespread sites accumulates downstream. Downstream cumulative effects are determined by the magnitude and spatial distribution of sediment supply, transport rates, and the channel network characteristics that determine where and when sediment accumulates within the drainage basin.

Previous studies have established that large volumes of sediment can be temporarily stored and remobilized in landscapes affected by accelerated erosion. In humid, eastern regions of North America, historical agricultural practices have produced large volumes of fine sediment (dominantly sand, silt and clay) that have accumulated on hillslopes, floodplains, and in heads of estuaries (Happ, 1945; Roehl, 1962; Trimble, 1974; Costa, 1975; Knox, 1977; Magilligan, 1985). Subsequent land-use changes can remobilize fine sediment from temporary storage, thus creating a lagged secondary wave of sediment load (Wolman, 1967; Jacobson and Coleman, 1986). Examples also exist in which large volumes of coarse bedload sediment are delivered directly to streams, either by human-induced causes such as mining (Gilbert, 1917; James, 1993) or natural causes such as volcanic lahars (Simon and Thorne, 1996). This sediment is also episodically stored and remobilized, causing ongoing adjustments to channel form (James, 1997). Coarse bedload sediment tends to remain in or near the channel where it can be remobilized by subsequent flows of sufficient magnitude, rather than being deposited in overbank areas far from the active channel. Because of higher transportation thresholds, coarse bedload sediment moves less frequently and for shorter distances than fine sediment.

Gilbert (1917) postulated that the coarse sediment delivered to streams from hydraulic mining in the Sierra Nevada progressed downstream as a coherent wave; this finding has been supported in general by more recent consideration of the mining debris (James, 1993, 1997). Meade (1985), Madej (1995), Nakamura *et al.* (1995) and Wathen and Hoey (1998) have noted similar wave-like movement of sediment, although the magnitudes and rates of translation and attenuation of sediment waves vary considerably because of differences in physiography, climate, sediment abrasion, and nature of the original disturbance.

Theoretical and experimental analyses of transport of gravel waves have addressed the relative roles of dispersion and translation in routing of sediment from points of delivery (Lisle *et al.*, 1997). These studies have shown that in straight laboratory flumes and one-dimensional transport models, wave-like influxes of sediment tend to disperse downstream more than they translate. Lisle *et al.* (1997) indicate, however, that in natural rivers other influences may allow downstream translation of coherent wave-like features after the initial form has decayed significantly.

Recent advances in computational models of sediment routing have focused on delivery of sediment from slopes to the channel and routing of fine, predominantly suspended-load sediment in relatively small drainage basins (Walling, 1988; Arnold *et al.*, 1995). These models emphasize delivery of sediment to a basin outlet rather than evaluating the effects of sediment delivery and storage along the channel within the basin. Little emphasis has been placed in these computational models on bedload movement and routing within large drainage basins and at scales where the channel network can contribute to augmentation or attenuation of sediment waves.

This report considers routing of gravel from widespread, low-intensity landscape disturbances in the Current River Basin, Missouri (Figure 1). The Current River Basin has undergone a land-use history that is typical of the Ozark Plateaus Physiographic Province (known locally as the Ozarks). Land use since European settlement has delivered substantial quantities of gravel to low-order streams (Saucier, 1983; Jacobson and Primm, 1997; Jacobson, 1995). Downstream accumulations of land-use-derived gravel have been associated with channel instability, bank erosion, and degradation of aquatic habitat (Hall, 1958; Love, 1990). Because gravel also has substantial economic value as construction aggregate, there is interest in identifying channel reaches with excess gravel (that is, gravel that has accumulated in greater volume than it would under a natural balance of supply and transport) where extraction of aggregate might have minimal negative effects on the aquatic ecosystem. The objective of this report is to evaluate the longitudinal distribution of gravel

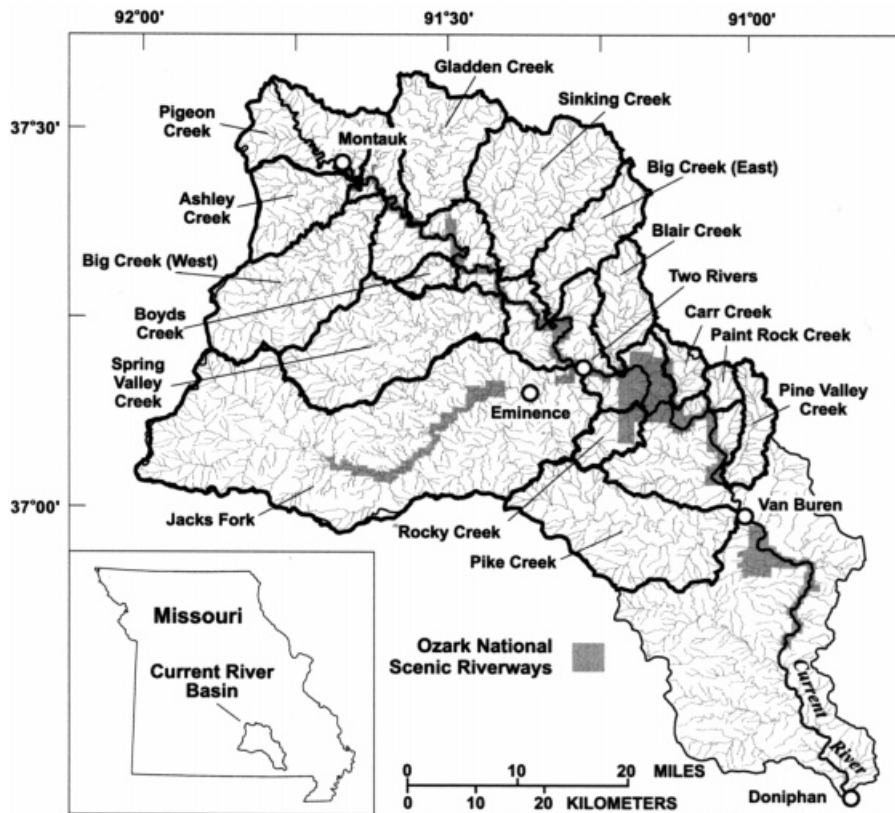


Figure 1. Location of the study segment of the Current River within the Current River Basin and tributary basins

along the mainstem of the Current River and determine the spatial and historical factors that have resulted in gravel accumulations.

#### PHYSIOGRAPHY AND HYDROLOGY OF THE CURRENT RIVER DRAINAGE BASIN

The Current River Basin (Figure 1) drains parts of the Salem Plateau of the Ozarks. It joins with the Black and White Rivers in Arkansas and flows southward into the Mississippi River. This report is concerned with the Current River upstream from Doniphan, Missouri, where the drainage area is approximately 5200 km<sup>2</sup>; this part of the basin is contained entirely within the Ozarks in Missouri.

The basin is underlain mostly by cherty carbonate bedrock of Palaeozoic age. Small areas of Precambrian metavolcanic rocks form prominent knobs and narrow, bedrock-confined valleys. The highest elevation in the upper basin is approximately 472 m a.s.l. (metres above sea level) and the elevation of the channel at Doniphan is approximately 100 m a.s.l. Reach-averaged channel gradients in the river segment considered here range from 0.05 per cent to 0.3 per cent; individual riffles have local gradients of as much as 1 per cent. Typical valley-floor to ridgetop relief is 150 m. A longitudinal profile of channel elevation is shown in Figure 2A.

The climate of the Ozarks is humid temperate with average annual rainfall ranging from 1000 to 1200 mm and average annual temperature ranging from 15 to 18°C. Large floods generally are caused by intense rainfall during the winter or late spring; relatively impermeable soils contribute to 'flashy' runoff events. Because of an extensive karst drainage system, some parts of the landscape have stream channels that are dry

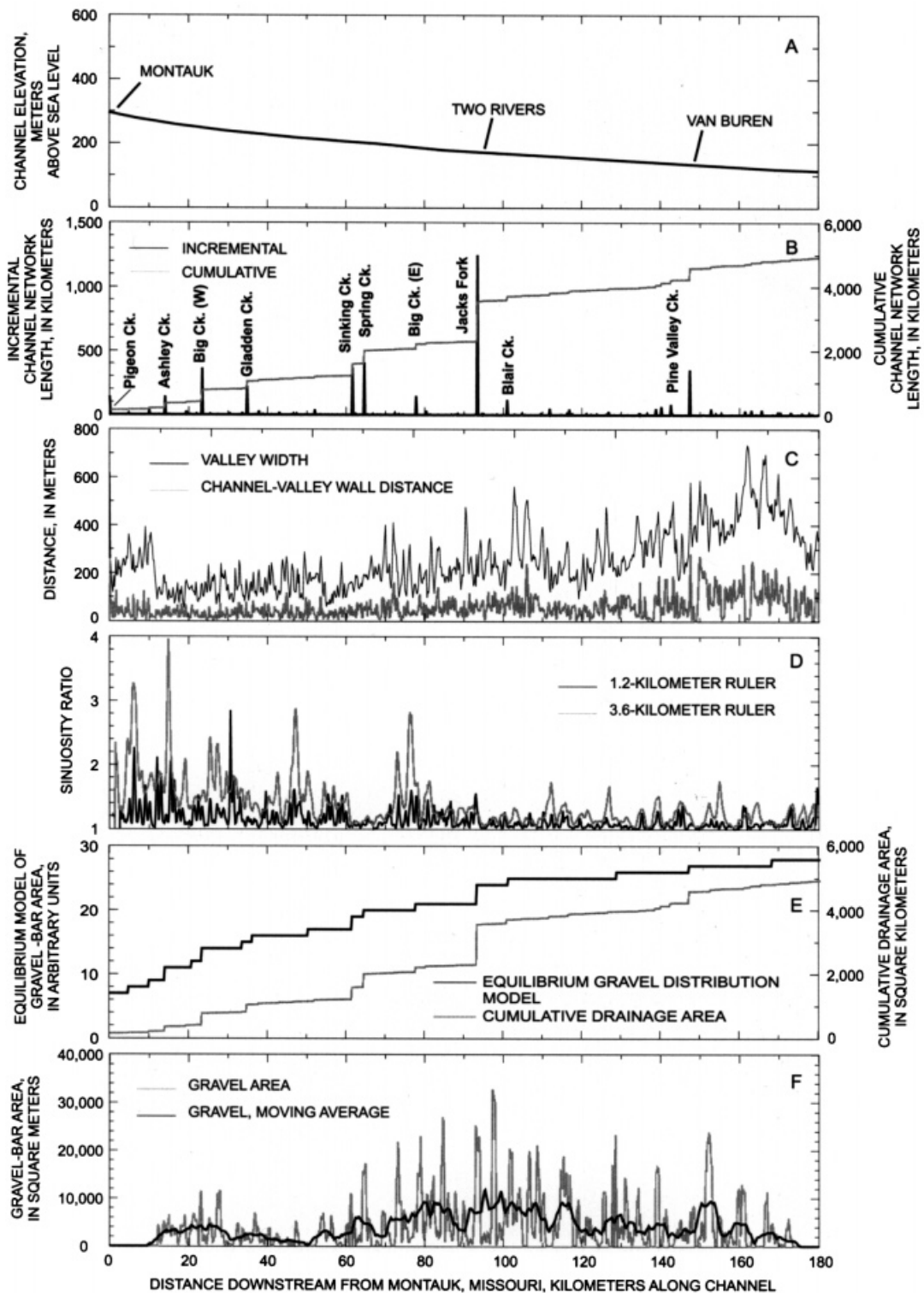


Figure 2. Longitudinal plots of the Current River mainstem characteristics, referenced to kilometres downstream from Montauk, Missouri. (A) Channel elevation. (B) Incremental and cumulative channel network length with selected tributaries labelled. (C) Valley width and distance from channel to valley wall. (D) Channel sinuosity ratio using 1.2 km and 3.6 km rulers. (E) Equilibrium gravel distribution model and cumulative drainage area. (F) Gravel-bar area and 25-point moving average

Table I. Hydrologic characteristics at streamflow gauging stations, Current River

Basin	River	Station	Station number	Period of record	Drainage area (km <sup>2</sup> )	Channel slope near gauge (m m <sup>-1</sup> )	Mean annual discharge per unit area (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Discharge exceeded 10 per cent of the time per unit area (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Maximum daily discharge of record per unit area (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Ratio of discharge on 3/8/92 to mean annual discharge
Current River	Jacks Fork Current River	at Eminence	07066000	Oct. 1921 – Nov. 1994	1019	0.00147	0.01	0.02	0.67	0.87
		near Eminence*	07066500	Aug. 1921–Sep. 1975	3256	0.00054	0.01	0.02	0.49	
		at Van Buren	07067000	July 1921–Nov. 1993	4268	0.00074	0.01	0.02	0.42	0.92
		at Doniphan	07068000	July 1921–Nov. 1994	5217	0.00049	0.02	0.03	0.49	0.80

\* This gauge is located at Two Rivers, immediately downstream from the junction of the Jacks Fork with the Current River. Operation was discontinued in 1975

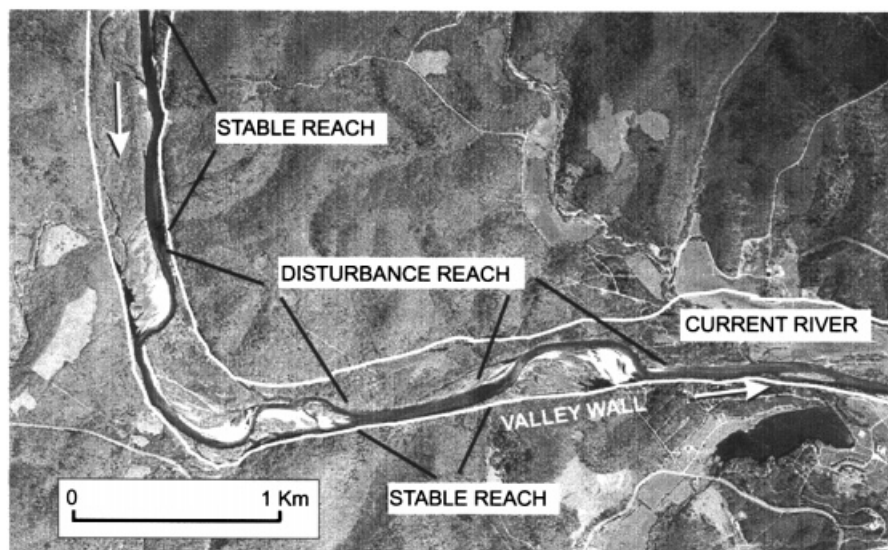


Figure 3. Current River immediately upstream from Van Buren, Missouri (137 to 143 km downstream from Montauk, Missouri). Stable reaches alternate with disturbance reaches (sedimentation zones of Saucier (1983)). Aerial photography taken 8 March 1992

most of the time, whereas other parts of the drainage network are supplied with substantial baseflow from springs. Flow in the Current River mainstem is sustained by many large springs, including Alley Spring on the Jacks Fork ( $3.5 \text{ m}^3 \text{ s}^{-1}$  mean discharge), Blue Spring ( $3.9 \text{ m}^3 \text{ s}^{-1}$  mean discharge) and Big Spring ( $12.1 \text{ m}^3 \text{ s}^{-1}$  average discharge) (Vineyard and Feder, 1974). Hydrologic data for USGS streamflow gauging stations on the Current River are summarized in Table I.

Valley widths and valley sinuosities in the Ozarks vary according to controls exerted by bedrock and karst drainage systems. On the Current River, valley width generally increases downstream, but the trend is interrupted by areas of anomalously narrow valley, controlled in part by outcrops of erosion-resistant Precambrian metavolcanic rocks (Figure 2C). The upstream one-quarter of the valley is maintained in a relatively narrow canyon cut into especially soluble dolomite. Channel sinuosity (measured continuously over 1.2 and 3.6 km distances) generally decreases downstream, but sinuosity is also highly variable over short distances (Figure 2D).

Channel patterns of Ozarks streams (Figure 3) are characterized by juxtaposed stable and disturbance reaches (Jacobson, 1995). The disturbance reaches originally were called sedimentation zones by Saucier (1983), and they are similar to sedimentation reaches described by Church (1983) in British Columbia. Because these reaches are characterized by erosion as well as sedimentation—and to avoid the perception that

they are dominated by sedimentation alone—we have elected to call them disturbance reaches. Church (1983) determined that the sedimentation reaches in British Columbia were caused mostly by external factors such as increased sediment load at tributary junctions. In the Ozarks, however, disturbance reaches are independent of tributary junctions, inputs of sediment from hillslope erosion, or structural and lithologic bedrock controls. Stable reaches tend to be long and straight, and the channel usually is adjacent to the valley wall on one side. The other side of the channel, however, is frequently adjacent to a broad, erodible, alluvial valley bottom; hence, the straight reaches do not appear constrained by bedrock control. Disturbance reaches are characterized by high sinuosity, frequent channel migration of as much as 250 m in 50 years (Jacobson and Pugh, 1997), and extensive, unvegetated gravel bars. Although the origins of disturbance reaches are obscure, we believe that they result from hydraulic interactions between the channel and the valley wall that cause localized constrictions, expansions, and flow separations at discharges substantially greater than bankfull. Data presented in the following sections on the longitudinal distribution of gravel on Current River indicate that disturbance reaches (a) are spaced at distances along the channel much greater than would be expected for meanders or alternate bars, and (b) are associated in part with reaches where bedrock-controlled valley widths are wider than average.

#### LAND-USE HISTORY AND CHANNEL DISTURBANCE OF THE CURRENT RIVER DRAINAGE BASIN

Pre-settlement vegetation of the Current River Basin was a mosaic of yellow pine forest, oak savanna, glades and prairie (Batek, 1994; Jacobson and Primm, 1997). Pine forests were dominant on the steep slopes along the Current River valley whereas oak savanna and patchy prairie dominated the rolling uplands away from the river. The understorey of the pine forest and oak savanna areas was open and dominated by grasses. The open nature of the woodland and the prairies and glades was maintained by wildfire (Guyette and McGinnes, 1982). After an initial increase in wildfire coincident with widespread settlement in the early 1800s, fire rates decreased precipitously, resulting in increased woody understorey and decreased area in prairie and glade vegetation (Ladd, 1991).

Early settlement of the Ozarks was concentrated along stream valleys where water provided transportation routes, domestic water supplies and water power. In the late 1800s, scattered family farms and small towns were joined by corporate timber-cutting operations that harvested yellow pine and oaks (Figure 4). In 1900, timber production in Missouri (mostly from the Ozarks) peaked at more than 700 million board feet. Human population and agricultural land use followed timber production in a boom and bust cycle (Rafferty, 1980; Stevens, 1991). Timber harvesting was widespread in the Current River Basin. By the 1920s, the valuable yellow pine had been harvested and the larger timber companies had moved on. They were replaced by smaller companies that harvested oaks mainly for the railroad tie market. With the loss of the timber economy, residents attempted to use the cut-over lands for agriculture, primarily grazing under open-range laws (Jacobson and Primm, 1997; Figure 4). During the period of open-range grazing, seasonal burning was used throughout the region in attempts to increase the value of forage. During the 1940s, the war-time economy encouraged row-crop agriculture in many Ozarks counties for a short time. However, low fertility, lack of mechanized equipment, and erodible soils resulted in limited success (Jacobson and Primm, 1997). Seasonal burning and open-range grazing decreased in the late 1950s to early 1960s as the open-range laws were repealed.

Cattle populations in the Ozarks have continued to increase to the present (1992; Figure 4), making Missouri the second largest cattle producer in the nation in 1996 (US Bureau of the Census, 1996). Also, starting in the late 1950s, second-growth timber began to be harvested in substantial quantities; this trend has continued into the 1990s. In 1965, approximately 100 km of the Current River valley was incorporated into the Ozark National Scenic Riverways under the management of the National Park Service (Figure 1). Since the inception of the Ozark National Scenic Riverways, riparian land use in the park has been limited to recreation and low-intensity forage management. Outside park property, land use has been dominated by timber management, grazing, low-intensity urbanization in several small towns, and scattered, low-intensity, in-stream gravel mining operations. In 1992, land-cover classification from Thematic Mapper satellite

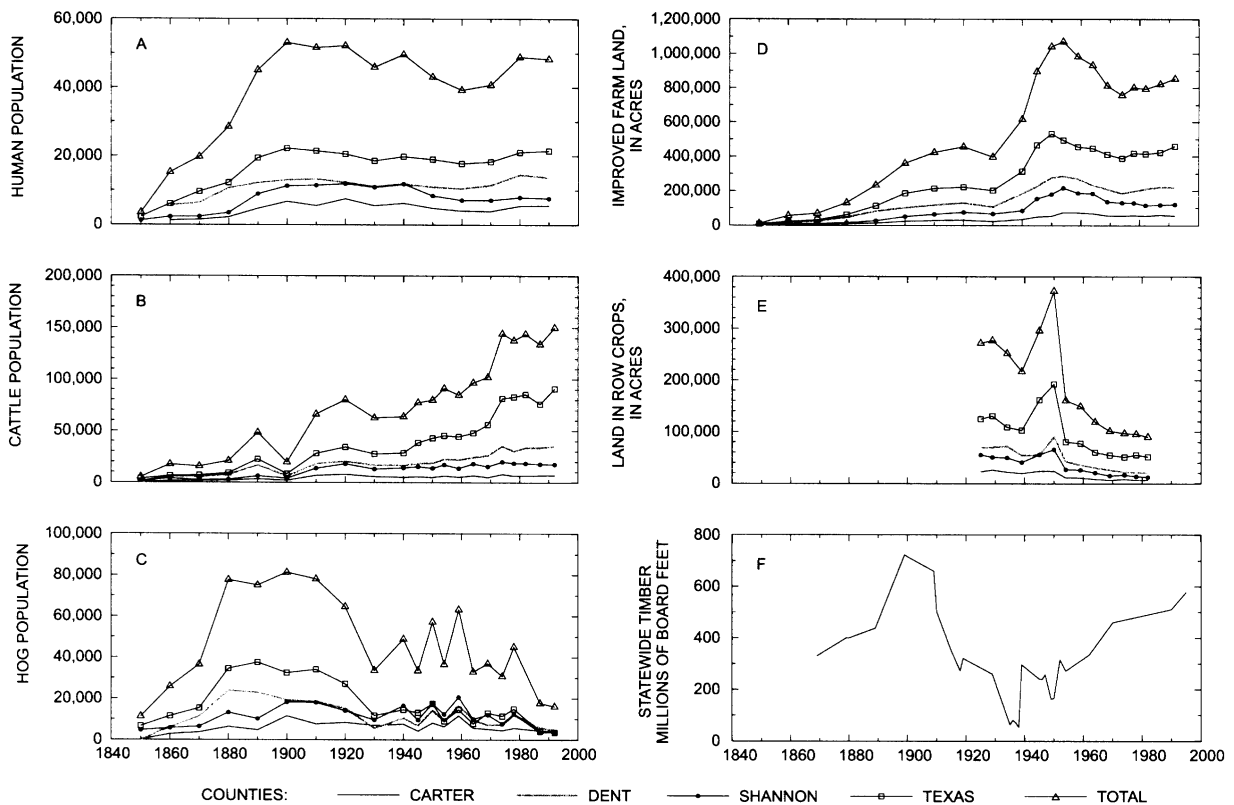


Figure 4. Census data for counties encompassing Current River Basin, Missouri. (A) Human population. (B) Cattle population. (C) Hog population. (D) Acres in farms. (E) Acres in row-crop cultivation. (F) Statewide timber production

imagery revealed that the basin-wide land use was approximately 82 per cent mixed deciduous forest, 14 per cent agricultural (mostly in pasture), 2 per cent evergreen forest, and 2 per cent barren plus urban land (Bobbitt, 1996).

Widespread and persistent anecdotal accounts have attributed gravel aggradation in Ozarks streams to land-use changes, particularly timber cutting (Krusekopf *et al.*, 1918; Baver, 1935; Hall, 1958). Saucier (1983) attributed sedimentation zones (disturbance reaches) to influxes of gravel derived from clear-cut lands. Regional stratigraphic studies (Jacobson and Pugh, 1992; Albertson *et al.*, 1995) document that valley bottoms of fourth-order Ozarks streams have increased volumes of gravel and sand in sediment of post-settlement age compared to the volumes of gravel and sand in pre-settlement deposits. These stratigraphic studies also indicate that post-settlement deposits have less fine sediment (silt plus clay) compared to pre-settlement deposits.

Systematic evaluation of available historical, stratigraphic and morphologic information indicated that timber-cutting methods at the turn of the century probably were insufficient to cause widespread gravel aggradation of Ozarks streams. Instead, Jacobson and Primm (1997) proposed that open-range grazing of cattle and hogs was the single most likely source of widespread disturbance of streams. They hypothesized that delivery of gravel to streams resulted from widening and upstream extension of first-order streams into previously unchannelled valleys. Jacobson and Primm (1997) also speculated that fine sediment was lacking in post-settlement deposits because open-range grazing in the riparian zone had decreased the ability of colonizing willows and sycamores to trap fine sediment.

Another likely mechanism for gravel delivery to streams is channel incision because of runoff associated with the rural road network. Observations by the authors and others (Scott Sowa, University of Missouri, oral

commun., 1997) indicate that many of the most deeply incised first-order channels on the present-day Ozarks landscape originate at road culverts. Incision into gravel-rich colluvium and alluvium at these sites may effectively extend the stream network and supply substantial quantities of gravel to streams. Whether the erosion was initiated by livestock effects on streams or by roads, the pathway for delivery of gravel to low-order streams has been direct, and initial response of streams was probably rapid.

The conceptual model of gravel transport from widespread, low-intensity landscape disturbance is supported by the history of streambed elevation changes from 1920 to 1994 (Jacobson, 1995). Streambed elevations in small drainage basins ( $<1400 \text{ km}^2$  area) generally decreased and stabilized during this time, whereas streambed elevations at mid-size drainage basins ( $1400\text{--}7000 \text{ km}^2$ ) are characterized by multiple waves of aggradation and degradation; streambed elevations of drainage basins greater than  $7000 \text{ km}^2$  generally were stable or slightly degrading. Jacobson (1995) interpreted these data as evidence that a substantial quantity of gravel had been transported from low-order drainage basins and was accumulating in mid-sized drainage basins. Lack of aggradation in large drainage basins indicated that the waves of land-use-derived gravel had not yet reached larger streams.

Jacobson (1995) also hypothesized that the vertical expression of gravel waves varied with reach-scale channel morphology and with channel network characteristics. Streamflow gauging stations in stable reaches showed only small waves of aggradation because bedload is transported efficiently through these long, straight reaches. Streamflow gauging stations placed in disturbance reaches, characterized by channel migration, tended to show much more pronounced waves of aggradation because of episodic storage and remobilization of bedload. In addition, streamflow gauging stations in dendritic parts of the drainage network appeared to have larger waves of aggradation than stations in networks with trellis structures. Dendritic networks were considered more likely than trellis networks to have cumulative bedload augmentation at channel junctions because of the increased likelihood that waves of bedload will arrive at tributary junctions at nearly the same time.

## METHODS

To develop a synoptic overview of gravel in transport in the Current River Basin, a longitudinal inventory of gravel-bar area was developed for 160 km of the mainstem by mapping from low-altitude aerial photographs (Figure 3). The photographs were scanned and georeferenced according to photo-identifiable points with known positions, and gravel deposits were mapped using automated image-processing classification and visual identification. The photographs were taken during a leaves-off period on 8 March 1992. The discharge on that day was  $52 \text{ m}^3 \text{ s}^{-1}$  at Van Buren, Missouri, slightly less than the mean annual discharge of  $55 \text{ m}^3 \text{ s}^{-1}$  (based on 83 years of record; Hauck *et al.*, 1996). Flow frequency along the stream segment was relatively constant (Table I), so gravel-bar inventories are not biased by varying hydroperiod.

The distribution of gravel along the river was inventoried in a longitudinal framework by defining address points at 200 m intervals along a digital representation of the centreline of the mainstem channel (Figure 5). Gravel areas were assigned to each address point by intersecting circular areas of 250 m radius centred at each address point with the mapped gravel bars. This method ensures that all gravel along the channel is inventoried, but oversamples slightly in reaches where gravel bars are close together. The addressing system allows channel, valley and basin characteristics to be associated with each point on the mainstem, thereby allowing a nearly continuous evaluation of factors that potentially affect channel dynamics (Figures 2 and 5).

The utility of gravel-bar area as a measure of gravel in transport through the river system is based on the assumption that gravel-bar area is a useful index of gravel volume. Certainly, volume is underestimated by a factor equal to the thickness of the gravel bar. To the extent that gravel thickness is constant or proportional to bar area, the longitudinal trends in bar area will underestimate volume but still show valid longitudinal patterns. If gravel thickness decreases while area increases, then areal inventories would not be a valid measure of longitudinal variation in sediment volume. Although quantitative data on gravel bar thicknesses are lacking, field observations along the Current River have not indicated a decrease in bar thickness with increase in bar area, or the presence of hydraulic or geologic controls that would produce anomalously thin bars.



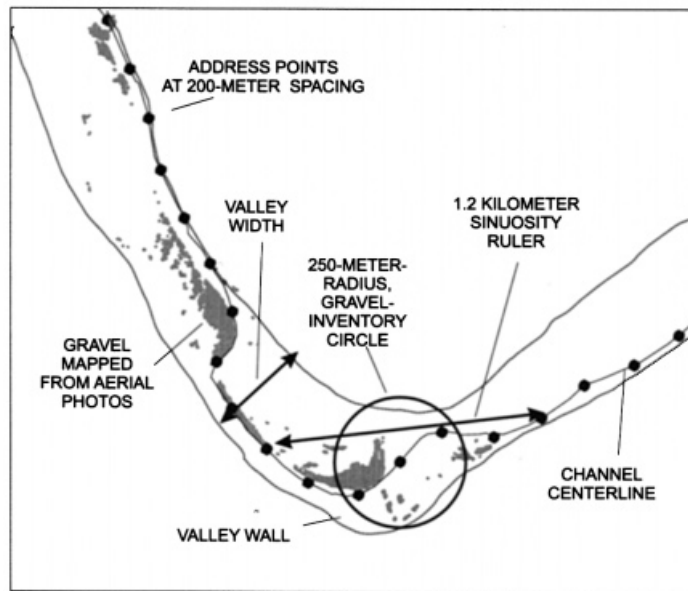


Figure 5. Addressing scheme and examples of measurements attributed to address points

Additional spatial data were collected using standard geographic information system (GIS) techniques. The channel network was compiled from 1:100 000 scale river-reach files (US Environmental Protection Agency, 1994); streams symbolized in this dataset are nearly identical to those depicted on 1:24 000 topographic quadrangles. Because drainage densities derived from 1:100 000 scale hydrologic network data are almost exactly equal to 1 in the Ozarks (Jacobson, 1995; Table II), incremental channel network length can be used to estimate contributing drainage area along the mainstem. Incremental network lengths for address points on the mainstem are as small as 200 m for address points with no tributary junctions between them, and the values increase with the size of tributary drainage area added between successive address points. Bedrock geology was digitized from 1:500 000 scale state maps (Missouri Division of Geology and Land Survey, 1979). Land use was classified from clustered Thematic Mapper satellite data (EOSAT, 1992). Roads were mapped from 1:100 000 scale USGS digital line graph data (US Geological Survey, 1990). Valley walls were compiled and digitized from 1:24 000 scale USGS topographic quadrangles. Although the resolution and accuracy of these data sources vary, the combined accuracy of the dataset is considered to be sufficient for the regional assessments over the 160 km length of the study channel.

## RESULTS AND DISCUSSION

We considered three hypotheses to explain the highly variable, wave-like distribution of gravel bars along the Current River (Figure 2F). The first hypothesis attributes accumulations of gravel to valley-scale characteristics that would promote longitudinal zones of storage. The second hypothesis attributes accumulations of gravel to increased input from tributary basins due to geologic, geomorphic or land-use conditions in the tributaries. The third hypothesis holds that gravel accumulations arise from channel network controls on time of arrival of gravel sediment routed from uniform disturbance in the drainage basin. The first two hypotheses are explored through statistical analysis of association of gravel with possible explanatory variables. The last hypothesis was explored by comparing the actual gravel distribution to distributions simulated from a simple, gravel-routing model.

Table II. Morphometric, land-use and geologic characteristics of tributary drainage basins, Current River

Basin	Drainage area (km <sup>2</sup> )	Total drainage length (km)	Drainage density (m km <sup>-2</sup> )	Basin relief (m)	Basin relief ratio (m km <sup>-2</sup> )	Main channel length (km)	Channel relief ratio (m km <sup>-1</sup> )	Channel slope (m km <sup>-1</sup> )	Basin width (km)	Length to width ratio (m m <sup>-1</sup> )	Road density (m km <sup>-2</sup> )
Ashley Creek	140.2	144.1	1.0	140	1.0	35.1	4.4	4.6	4.0	8.8	1.2
Big Creek (East)	153.8	147.8	1.0	220	1.5	43.9	5.2	4.4	3.5	12.5	1.1
Big Creek (West)	333.3	367.7	1.1	180	0.5	53.5	3.6	2.7	6.2	8.6	1.1
Blair Creek	110.6	119.0	1.1	200	1.7	30.6	6.8	5.5	3.6	8.5	1.3
Boyd's Creek	33.5	40.5	1.2	160	4.0	13.3	12.0	10.2	2.5	5.3	0.7
Carr Creek	47.1	46.4	1.0	180	3.9	16.4	10.7	8.9	2.9	5.7	1.4
Gladden Creek	222.0	224.2	1.0	180	0.8	46.3	3.9	3.7	4.8	9.7	1.1
Jack's Fork	1156.0	1257.0	1.1	300	0.2	104.6	2.6	1.9	11.0	9.5	1.3
Pike Creek	362.7	362.8	1.0	220	0.6	60.2	3.3	2.9	6.0	10.0	1.2
Pine Valley Creek	76.9	83.1	1.1	180	2.2	23.4	7.7	6.1	3.3	7.1	0.8
Rocky Creek	61.3	51.9	0.8	220	4.2	18.4	8.2	7.5	3.3	5.5	1.1
Sinking Creek	329.3	372.8	1.1	220	0.6	42.5	5.0	3.5	7.8	5.5	1.0
Spring Valley Creek	366.0	414.1	1.1	220	0.5	67.1	3.5	3.0	5.5	12.3	1.2

Basin	Urban plus barren land (per cent area)	Agricultural plus range land (per cent area)	Forest land (per cent area)	Meta-volcanic rocks (per cent area)	Cherty-dolomite (per cent area)	Sandstone and cherty-dolomite (per cent area)	Argillaceous dolomite (per cent area)	Other rocks (per cent area)	Gravel inventory in active bars at mainstem (m <sup>2</sup> )	Gravel inventory in active bars summed 1 km downstream (m <sup>2</sup> )
Ashley Creek	1.7	22.2	76.0	0.0	37.3	62.7	0.0	0.0	4366	19 373
Big Creek (East)	0.7	6.1	93.0	0.0	92.9	7.1	0.0	0.0	4407	52 356
Big Creek (West)	2.3	26.8	70.9	0.0	12.8	42.6	44.5	0.0	3098	9 294
Blair Creek	0.0	3.0	96.8	2.4	89.6	8.0	0.0	0.0	3978	57 801
Boyd's Creek	0.0	4.5	95.5	0.0	34.7	65.3	0.0	0.0	0	4 920
Carr Creek	0.6	6.9	92.6	0.0	89.4	10.6	0.0	0.0	8601	46 234
Gladden Creek	6.9	32.8	60.3	0.0	56.3	43.7	0.0	0.0	1204	7 080
Jack's Fork	1.4	20.7	77.8	0.0	26.0	72.7	1.2	0.1	20 180	88 303
Pike Creek	2.0	12.8	85.2	0.0	80.0	19.6	0.0	0.4	4344	27 167
Pine Valley Creek	1.1	11.3	87.7	24.3	67.8	7.9	0.0	0.0	31	1 362
Rocky Creek	0.8	11.8	87.3	0.0	90.9	9.1	0.0	0.0	78	1 191
Sinking Creek	1.5	18.9	79.4	0.0	24.5	42.8	32.7	0.0	98	14 932
Spring Valley Creek	2.0	33.0	64.9	0.1	26.1	43.7	30.1	0.0	14 980	55 541

### *Longitudinal distribution of gravel related to valley-scale characteristics*

The longitudinal distribution of gravel along the Current River mainstem is highly variable (Figure 2F) and seems to vary significantly at five to seven prominent periods (Figure 6). Peaks with short spacings (shown by the gravel-bar areal inventory curve, Figure 2F) are superimposed on a broad, multi-peak trend (shown by moving-average curve, Figure 2F). Inspection of aerial photography shows that the prominent short-spacing peaks are coincident with disturbance reaches. Spectral analysis of the gravel distribution data indicates three significant quasi-periodic signals (99 per cent confidence limit) at 1860, 2155 and 4015 m (Figure 6). In this analysis, the gravel distribution over space was treated like a time series—the data were detrended and the mean was adjusted to zero before spectral analysis using the multi-taper method and code developed by Mann and Less (1996). The significance of power at each frequency was computed by comparison to a red noise background. Estimation of significant quasi-periodic signals in this dataset was found to be insensitive to method of detrending and choice of red or white noise backgrounds. Frequencies in the spectral distribution have been converted to equivalent periods (spacings) in metres along the channel (Figure 6).

If these prominent spectral peaks were related to channel meanders, they would be expected to have a spacing of about 11 to 16 times the channel width, according to conventional channel-geometry models (Leopold *et al.*, 1964). For the typical range of bankfull widths on this segment of the Current River, this spacing would range from 70 to 450 m. Peaks in the distribution with these low spacings may be present, but the 200 m spacing of address points on the mainstem does not allow accurate evaluation of any spacings less than 400 m. Because the prominent spacings at 1375–4015 m (and greater) are at a substantially greater spacing than would be expected from channel meandering, we conclude that they are associated with a different process, probably controlled in part by valley-scale geologic constraints.

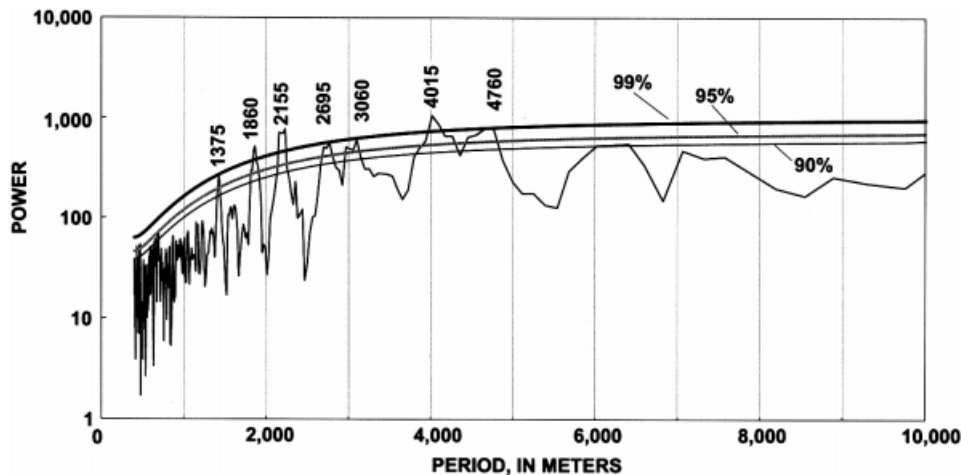


Figure 6. Power spectrum of gravel-bar distribution by period (spacing) along the channel. Confidence levels are for the amplitude of the quasi-periodic signals compared to a red noise background model (Mann and Lees, 1996)

Geologic constraints alone, however, are not sufficient to explain the magnitudes of accumulations with spacings of 1375–4015 m. Some of these peaks are coincident with tributary junctions, but many more are not (Figures 2F and 7A). In some locations, gravel peaks seem to relate to increased valley widths (for example river km 70–110). When plotted against valley width, gravel area shows an envelope relation with a peak corresponding to a valley width of about 250 m (Figure 7B). Many locations, however, have gravel areas much less than the envelope, and the widest downstream valleys have smaller areas of gravel than valleys of intermediate width (for example, river km 150–170). Visual and statistical comparisons of gravel areas and 1.2 and 3.6 km channel sinuosity reveal no apparent associations between channel sinuosity and gravel area. Numerous multivariate statistical analyses (not presented here) have failed to discern any significant relations among gravel-bar area and valley-scale characteristics.

#### *Longitudinal distribution of gravel related to tributary basin characteristics*

As a 'first order' of approximation, the broad, multi-peak trend of the gravel distribution seems to reflect the sequence and size of tributary basin inputs from upstream to downstream. For example, the large gravel-bar area near river km 94 is coincident with the junction of Jacks Fork; less gravel-bar area occurs upstream and downstream where tributary drain basins are smaller. In general, however, gravel-bar areas at address points along the mainstem are associated only weakly with channel network lengths (Figure 7A). Nine peaks in the gravel-bar areal inventory correspond with particular tributary junctions, but most peaks do not. At these addresses, highly variable gravel-bar areas correspond with small incremental network lengths.

The contributions of 13 individual tributary drainage basins of more than 30 km<sup>2</sup> area were considered in greater detail by plotting gravel inventories summed over 1 km downstream from tributary junctions against selected tributary characteristics (Figure 8 and Table II; product-moment correlation coefficients are given in Table III). This analysis is limited to descriptive statistics. Multivariate regression models or analyses of variance were unwarranted because of uncertainties inherent in determining how much gravel in the mainstem should be associated with each tributary and because of the small sample size.

Most of the morphometric variables vary collinearly because of the effect of drainage area. Among the morphometric variables, gravel-bar area seems to increase with drainage area and basin relief. None of the relations is particularly strong, and the relation with drainage area is mostly dependent on one point representing the Jacks Fork tributary. Morphometric variables describing basin slope (channel slope and basin relief ratio) have weak inverse relations with gravel-bar area because they are calculated with channel length or drainage area in the denominator. Among land-use intensity variables, only road density (length of roads per basin area) seems to have a systematic direct relation with associated gravel-bar area. These

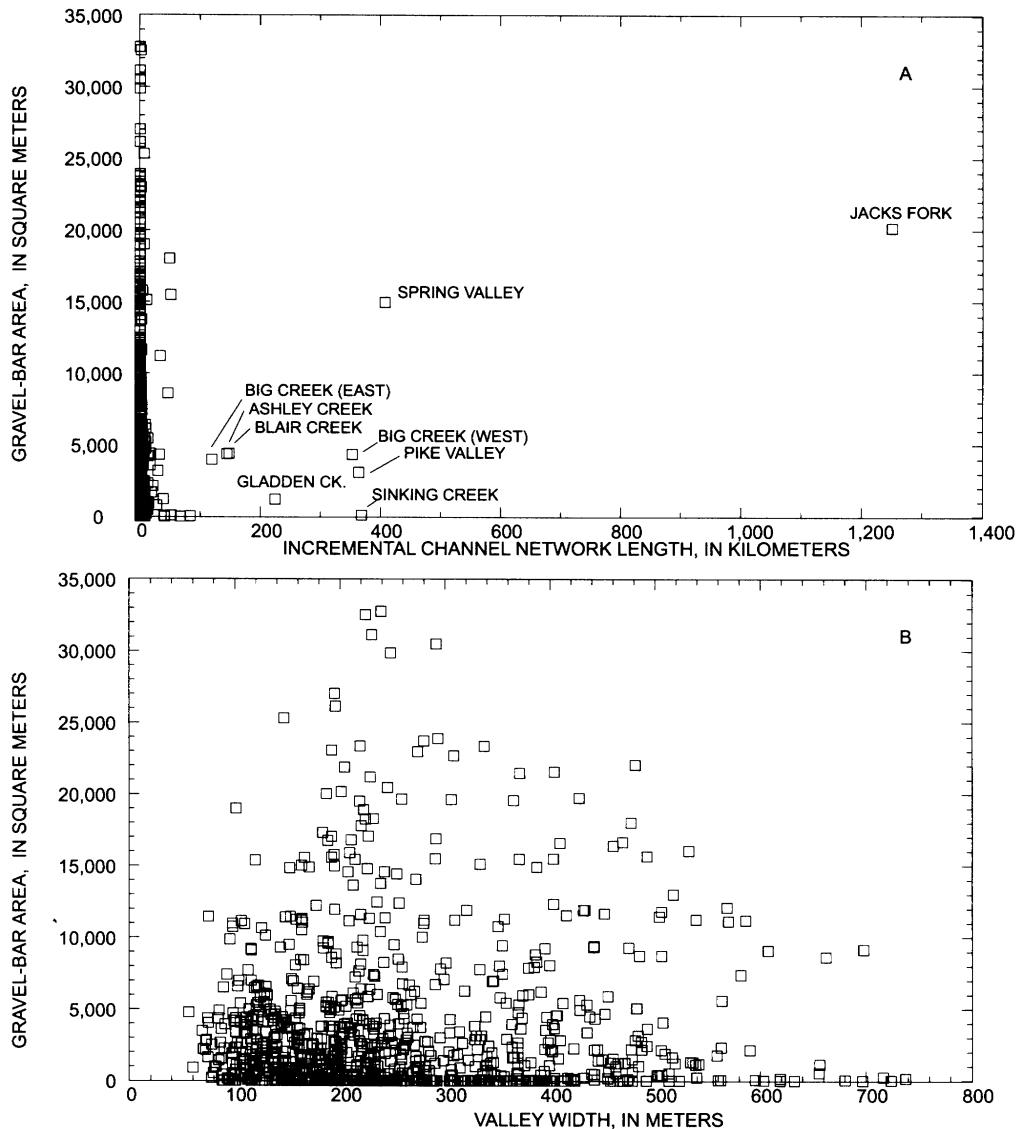


Figure 7. Scatter diagrams of (A) gravel-bar area and incremental drainage network length for all address points, and (B) gravel-bar area and valley width

relations indicate generally weak relations between mainstem gravel-bar area and tributary drainage-basin characteristics.

The lack of strong relations between gravel-bar area and tributary-basin land use probably results from several factors. Valley-scale controls on gravel accumulations in the mainstem may mask some effects of individual tributaries. In addition, gravel contributed from each tributary basin over the past 160 years may be spread out along the channel within the tributary basin and for some variable distance downstream in the mainstem. If so, the sum of gravel associated with each tributary basin at any particular time may be highly dependent on the history of transport from the basin.

#### *Longitudinal distribution of gravel compared to routing from a uniform disturbance*

A simple gravel routing model was developed to evaluate how the history of transport of gravel through the Current River could be reflected in a synoptic distribution of gravel bars along the mainstem. The model uses

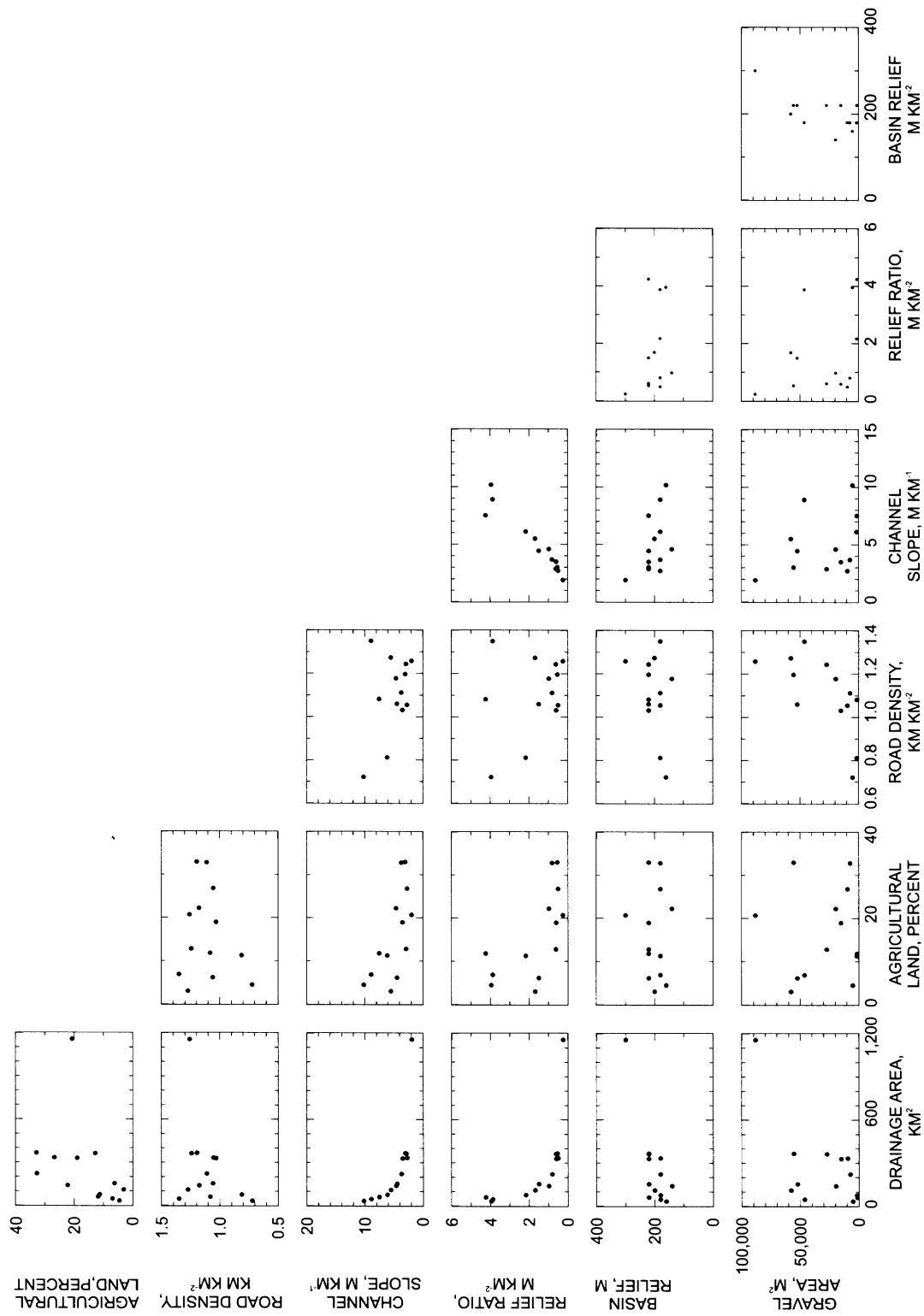


Figure 8. Scatter plots of gravel-bar area summed for 1 km downstream from selected tributary junctions and selected morphometric and land-use characteristics

Table III. Pearson product-moment correlation coefficients for selected tributary characteristics

	Total drainage length	Drainage density	Basin relief	Basin relief ratio	Main channel length	Channel relief ratio	Channel slope	Basin width	Length to width ratio	Road density	Urban + barren (per cent)	Agricultural + range (per cent)
Total drainage length	1.00											
Drainage density	1.00	1.00										
Basin relief	0.21	0.24	1.00									
Basin relief ratio	0.80	0.79	-0.10	1.00								
Main channel length	-0.61	-0.61	-0.29	-0.32	1.00							
Channel relief ratio	0.94	0.93	0.18	0.74	-0.78	1.00						
Channel slope	-0.64	-0.63	0.02	-0.44	0.93	-0.82	1.00					
Basin width	-0.67	-0.67	-0.07	-0.49	0.95	-0.84	0.99	1.00				
Length to width ratio	0.94	0.95	0.25	0.74	-0.70	0.89	-0.70	-0.76	1.00			
Road density	0.33	0.32	-0.06	0.28	-0.65	0.61	-0.70	-0.66	0.22	1.00		
Urban + barren (per cent)	0.34	0.33	-0.39	0.35	-0.29	0.41	-0.41	-0.38	0.31	0.34	1.00	
Agricultural + range (per cent)	0.15	0.14	-0.10	-0.08	-0.46	0.29	-0.51	-0.46	0.22	0.31	0.11	1.00
Forest (per cent)	0.39	0.40	0.15	0.07	-0.64	0.54	-0.69	-0.66	0.47	0.39	0.16	0.76
Meta-volcanic (per cent)	-0.37	-0.38	-0.12	-0.05	0.64	-0.52	0.69	0.65	-0.45	-0.39	-0.16	-0.82
Ch-dolomite (per cent)	-0.20	-0.20	0.11	-0.16	0.10	-0.24	0.19	0.14	-0.23	-0.15	-0.46	-0.12
Ss. and ch.-dolomite (per cent)	-0.47	-0.50	-0.71	-0.03	0.50	-0.46	0.37	0.40	-0.56	-0.02	0.23	-0.23
Argil. dolomite (per cent)	0.53	0.54	0.58	0.05	-0.36	0.46	-0.27	-0.25	0.52	0.02	-0.13	0.24
Other rocks (per cent)	0.17	0.20	0.43	0.04	-0.44	0.27	-0.37	-0.44	0.37	0.07	-0.05	0.12
Gravel at mainstem	0.42	0.39	-0.11	0.40	-0.32	0.46	-0.38	-0.37	0.40	0.24	0.31	0.05
Gravel summed 1 km	0.76	0.77	0.13	0.64	-0.37	0.76	-0.41	-0.41	0.59	0.47	0.58	-0.05

	Forest (per cent)	Meta-volcanic (per cent)	Ch-dolomite (per cent)	Ss. and ch.- dolomite (per cent)	Argil. dolomite (per cent)	Other rocks (per cent)	Gravel at mainstem	Gravel summed 1 km
Total drainage length								
Drainage density								
Basin relief								
Basin relief ratio								
Main channel length								
Channel relief ratio								
Channel slope								
Basin width								
Length to width ratio								
Road density								
Urban + barren (per cent)								
Agricultural + range (per cent)								
Forest (per cent)	1.00							
Meta-volcanic (per cent)	-1.00	1.00						
Ch-dolomite (per cent)	-0.18	0.18	1.00					
Ss. and ch.-dolomite (per cent)	-0.65	0.61	0.15	1.00				
Argil. dolomite (per cent)	0.51	-0.48	-0.35	-0.85	1.00			
Other rocks (per cent)	0.54	-0.49	-0.17	-0.67	0.23	1.00		
Gravel at mainstem	-0.04	0.03	-0.12	0.12	0.00	-0.19	1.00	
Gravel summed 1 km	0.30	-0.25	-0.25	-0.26	0.35	0.06	0.23	1.00

Ss., sandstone; Ch., chert; Argil., argillaceous

a network-based GIS for the Current River Basin to account for the arrival of gravel ‘packets’ at address points along the mainstem (Figure 9A). This simple, heuristic model is used to explore qualitative characteristics of the longitudinal distribution of gravel on the mainstem that would result from sediment routing from widespread, low-intensity disturbance in the channel network. Results of the model can be compared with the actual distribution of gravel and a distribution that would result if gravel bar areas scaled with discharge.

In a drainage basin where gravel transport is in some sort of dynamic equilibrium—such that sediment supply is balanced by sediment transport capacity—the area of gravel bars would be expected to scale with discharge. Based on regional flood-frequency models that show discharge of 2 year floods increasing with the 0.75 power of drainage area (Alexander and Wilson, 1995), gravel-bar area would be expected to increase at a decreasing rate downstream, with discrete increases at tributary junctions (Figure 2E). The linear constant of proportionality for this relation is unknown; the general shape of the longitudinal distribution, however, would not be affected by the constant. This distribution will be referred to as an equilibrium distribution (Figure 2E). The general monotonic form of this distribution would be altered locally by hydraulic effects on the scale of disturbance and stable reaches. Clearly, the actual gravel-bar area distribution does not scale with discharge (compare Figures 2E and F).

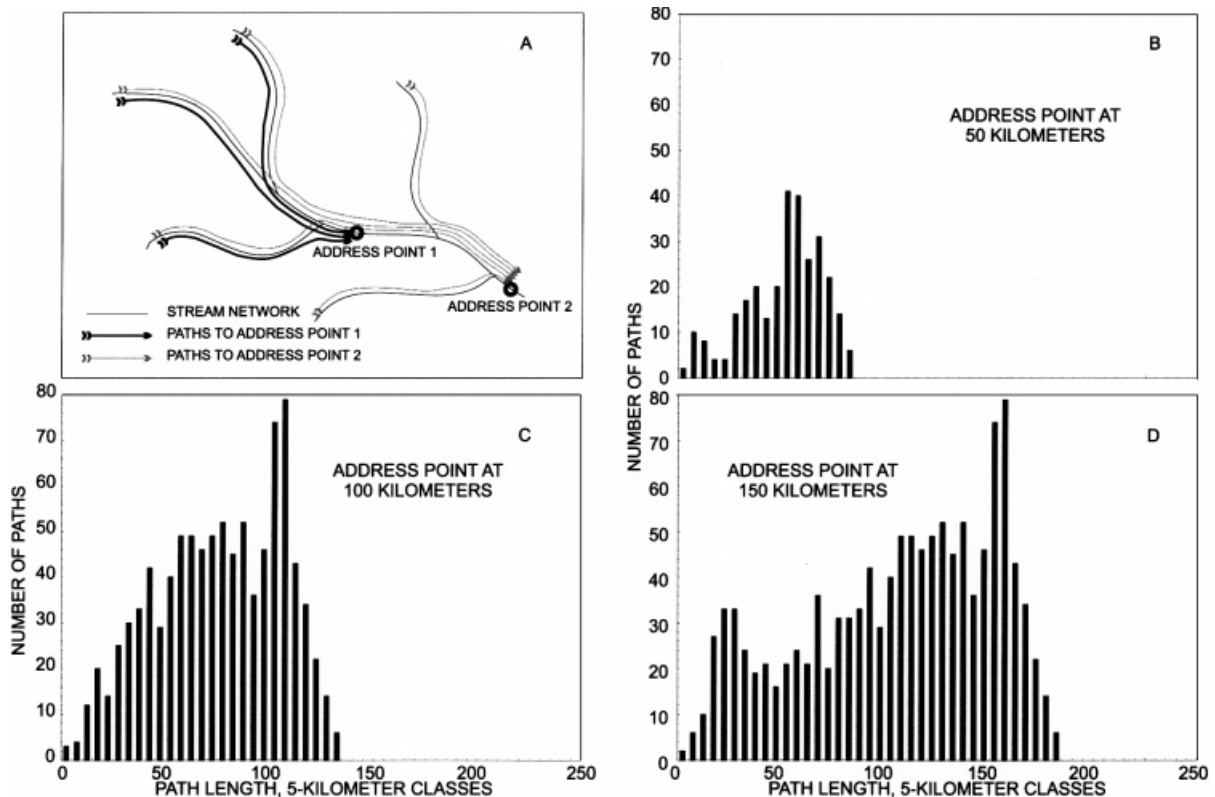


Figure 9. Definition and results of network-based gravel routing model. (A) Scheme for measuring all channel paths upstream from address points. (B) Frequency distribution of paths at address point at 50 km. (C) Frequency distribution of paths at address point at 100 km. (D) Frequency distribution of paths at address point at 150 km

Under land-use disturbance, delivery of gravel to the channel network at higher than natural rates would be expected to perturb the equilibrium distribution. The land-use history supports the idea that disturbance was widespread and most of the gravel was delivered primarily from headward extension of first-order tributaries; therefore the model assumes that gravel is delivered in uniform quantities (or 'packets') at the upstream ends of first-order tributaries. The delivery is also assumed instantaneous and followed by immediate stabilization of the gravel source areas.

The model is constructed by considering the routing of gravel from the extreme upstream ends of the channel network to address points on the mainstem. For each address cell along the mainstem, the arrival times of gravel packets are assumed to be directly proportional to the length of network paths upstream from the address points (Figure 9A). The path lengths were derived by tracing each possible network path upstream from the address points using standard GIS techniques (ESRI, 1992) and 1:100 000 scale hydrography. The distributions of paths upstream from each address point were then summarized by 5 km intervals (for example, Figure 9B–D).

Under the assumption of uniform gravel transport velocity, a path length is directly proportional to a time of arrival of a gravel packet released from first-order streams. For an interval of path lengths—representing an interval of arrival times—a graph of numbers of paths upstream from the 904 address points depicts a theoretical, synoptic longitudinal distribution of the quantity of land-use-derived gravel that arrives at each address point in that time interval (Figure 10).

The modelled distribution of land-use-derived gravel shows initial uniformity because of rapid delivery of gravel from short, low-order tributaries near the mainstem (Figure 10, timesteps 1–5). As time progresses, longer paths from larger tributaries begin to deliver gravel to the mainstem, resulting in peaks of gravel at and

downstream from tributary junctions. Finally, excess gravel is exhausted from upstream reaches, and gravel waves are translated through the mainstem section and delivered to downstream reaches (Figure 10, timesteps 17–35).

This model illustrates the potential for sediment to accumulate as a result of downstream routing and merging in a channel network, similar to routing and growth of flood waves, but on a longer time frame. The synoptic distribution of gravel in transport may accordingly relate to network structure and elapsed time as much or more than it relates to valley-scale or tributary basin characteristics. Despite the simple nature of the model, it produces many features in common with the actual distribution of gravel, especially near timesteps 7 to 9. Similar to the modelled distribution, the actual distribution has multiple peaks related to tributary junctions (indicated by peaks in the incremental channel network), and some peaks seem to have translated downstream from the junctions. The broad wave-like increase in gravel at, and downstream from, the Jacks Fork junction is also replicated in the model.

No gravel transport distance data exist for Ozarks rivers, but the implicit gravel transport distances do not seem unrealistic. At timesteps 7 to 9, path lengths are 30 to 45 km. The longest possible accumulation period would be approximately 160 years (1830 to 1992, if disturbance began at earliest settlement) and the shortest probable period of accumulation would be approximately 40 years (1950 to 1992, if disturbance began at the peak of agricultural cropland in the 1950s). These numbers equate to a range of gravel-particle transport rates of approximately  $190 \text{ m a}^{-1}$  to  $1125 \text{ m a}^{-1}$ . For comparison, tracer-based measurements of mean bedload particle travel on smaller rivers are in the range of 11–65 m per transporting event (Hassan *et al.*, 1991).

The uniform routing model is presented as an indication of the potential roles of channel-network structure and time in sediment routing. In actuality, the delivery and transport of gravel probably vary with many other factors in addition to path length; the processes and rates of erosion, transport and deposition certainly are more complex than presented in this simple model. Channel widening in downstream reaches would increase gravel yield over that assumed in the model. Increased opportunities for off-channel storage of gravel downstream might counteract this effect. Dispersion of sediment waves would diminish the magnitude of wave-like accumulations, but transient storage in disturbance reaches could work to reform waves. Abrasion of bed material could also diminish downstream impacts; however, the hard chert content of Ozarks streams is minimally susceptible to abrasion. Whereas source area recovery is assumed instantaneous in the model, new channels formed by headward extension might be expected to remain unstable, and therefore they may continue to deliver gravel at an accelerated rate. Of course, episodic, continued or non-uniform land-use disturbance would result in a more complex sequence of waves of gravel moving through the channel network. Variability in transport rates because of extreme floods or drainage-basin and channel characteristics, and variability in rates of revegetation of gravel bars, are other sources of variation not accounted for in this model.

Despite its simplicity, the routing model serves to illustrate that many of the features of the actual gravel distribution can be simulated with uniform routing of disturbance-induced sediment packets through the channel network. The broad wave-like increase in gravel bar area at km 60–120 does not necessarily require an explanation based on valley-scale characteristics or variations in disturbance history along the channel; this accumulation can be explained by lagged transport through the channel network. The gravelbar area peaks with spacings of 1375–4150 m can be considered secondary modifications related to valley-scale hydraulic controls that favour gravel accumulations in disturbance reaches. The available evidence supports the interpretation that the broad wave-like increase in gravel bar area at km 60–120 is excess gravel in transit in the Current River alluvial system.

## IMPLICATIONS AND CONCLUSIONS

In an undisturbed system, or a system in dynamic equilibrium, the gravel-bar area in bars would be expected to increase systematically downstream, similar to hydraulic geometry relations for channel width (Leopold *et al.*, 1964; Figure 2E). Deviation from the longitudinal form of this theoretical reference condition is an indication that substantial excess gravel exists in the sediment transport system. In the segment of the Current



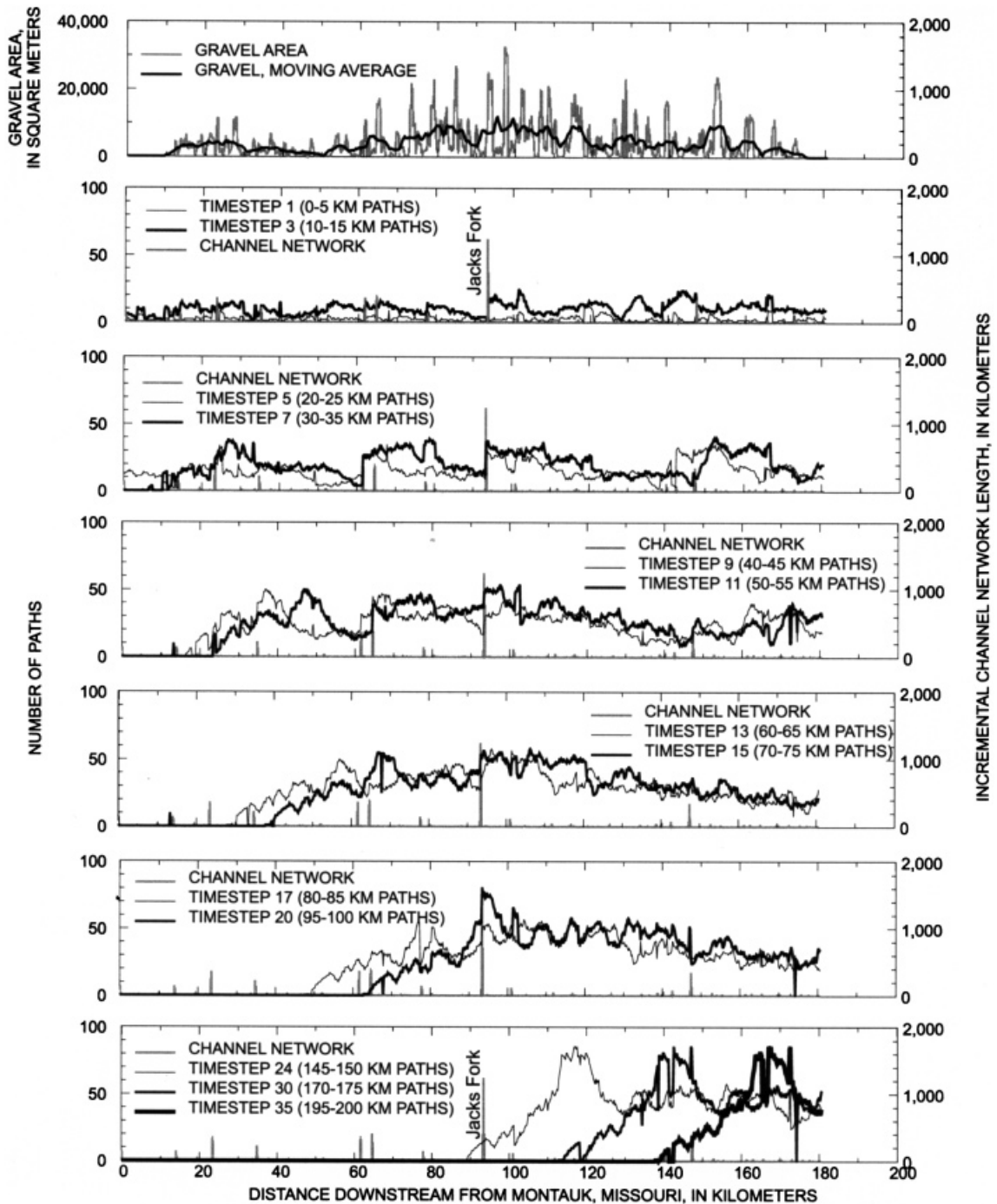


Figure 10. Longitudinal plots of gravel-bar area and numbers of paths of given lengths upstream from address points for various time steps. Incremental channel network length distributions are shown for reference

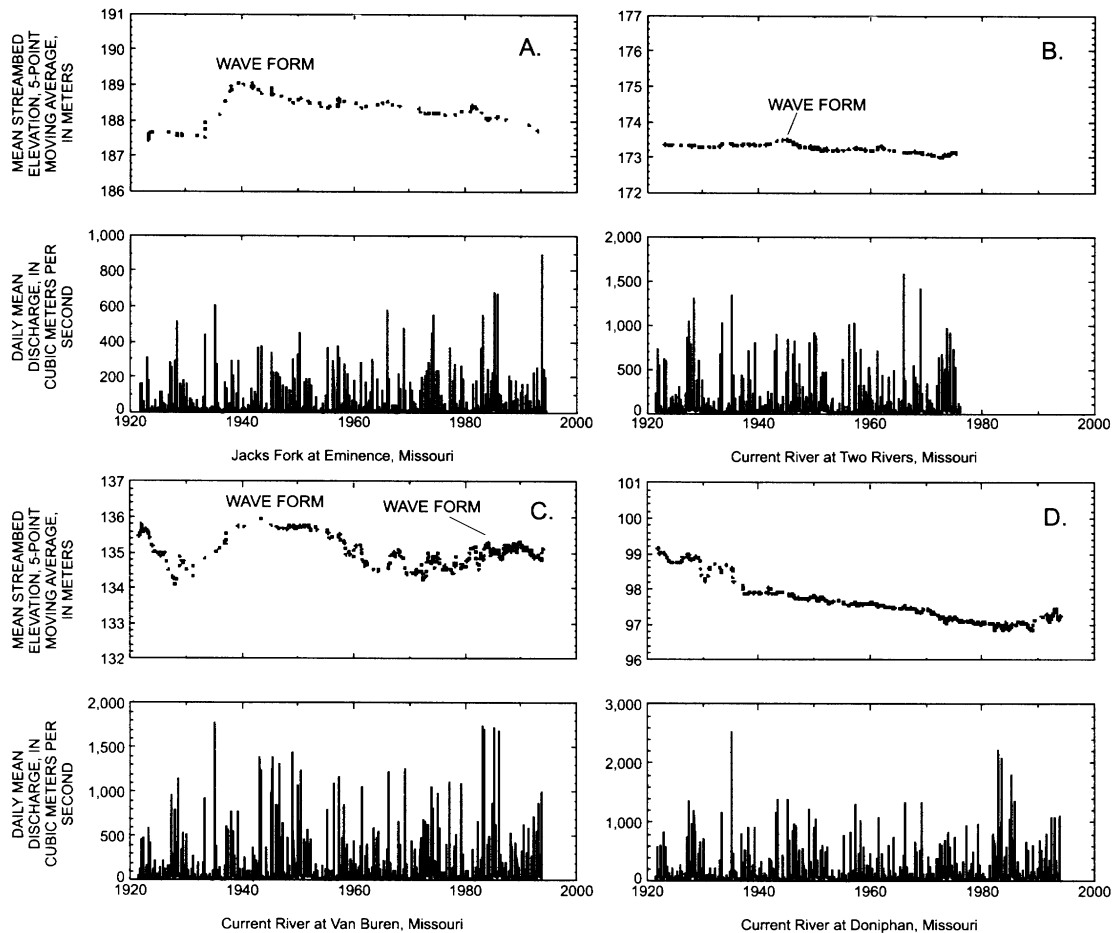


Figure 11. Mean streambed elevation changes for stream gauges in the Current River Basin, showing variations in aggradation responses. (A) Jacks Fork at Eminence, Missouri. (B) Current River near Eminence, Missouri (near Two Rivers, Missouri). (C) Current River at Van Buren, Missouri. (D) Current River at Doniphan, Missouri. From Jacobson (1995)

River studied, deviation from the equilibrium distribution occurs as a broadly defined concentration centred around the Jacks Fork and as multiple, shortly spaced peaks of gravel concentrations (Figure 2F).

Identification of excess gravel in the Current River Basin is consistent with other lines of evidence that have indicated that widespread, low-intensity land-use changes in the Ozarks have resulted in accelerated delivery of gravel sediment to streams and downstream passage of waves of gravel (Jacobson and Primm, 1997; Jacobson, 1995). For example, streambed elevation data from three USGS gauges on Current River (Figure 11A–C) show wave-like forms passing the gauges in the upper basin and middle of the study segment (Eminence on Jacks Fork, Two Rivers at river km 94, and Van Buren at river km 142). An increase in bed elevation followed by a decrease is evidence of passage of a sediment wave that has some component of translation; the relative contributions of dispersion and translation cannot be discerned from these records. Degradation of the bed at Doniphan, Missouri (Figure 11C, river km 205) is probably associated with historical improvements of the navigation channel downstream from that point; excess gravel load from upstream land-use disturbance has not yet reached Doniphan. The diminished wave form at Two Rivers (Figure 11B) results from the location of this streamflow gauging station in a stable reach where efficient transport of bedload minimizes the expression of bedload waves.

The simple sediment-routing model presented here indicates that the observed broad-scale distribution of gravel and downstream translation of gravel peaks could result from uniform transport of excess gravel

through a channel network. In such a model, the magnitude of gravel accumulation at a given place and at a given time primarily depends on position within the channel network. Variations in other tributary basin characteristics – such as present-day land use, morphometry and geology – are not necessary to explain the observed broad-scale gravel distribution. Tributary basin characteristics may well have an effect on gravel distributions, but within the range of variation that exists in the Current River Basin, only weak tributary effects are measurable. Present-day land use seems to be much less important than the propagating effects of historical land use in determining the present-day gravel distribution. Local hydraulic interactions between the channel and the valley – although poorly understood – exert a secondary effect, resulting in discrete gravel accumulations at the scale of disturbance reaches.

The gravel waves identified in the Current River at the segment scale (Jacobson, 1995) and reach scale (McKenney and Jacobson, 1996) are similar in some ways to bedload waves documented in the East Fork River in Wyoming by Meade (1985). The Current River waves differ in origin, however, because they were produced by widespread, low-intensity land-use change, whereas the waves on East Fork River were attributed to excessive sediment delivery from channel instability on a single tributary. Hence, bedload waves translating downstream in the Current River are augmented by additions of bedload waves at tributary junctions. In addition, the East Fork River waves are composed of sand transported over a stable gravel bed, so the mechanics of translation and dispersion may be substantially different from the Current River. The Current River gravel waves have some similarities as well to the well-documented waves of sediment associated with hydraulic gold mining in the Sierra Nevada (Gilbert, 1917; James, 1993). However, the Sierra Nevada case involved much greater sediment delivery from a few intensely mined source areas on the Yuba, Bear and American Rivers. Hence, the waves were much larger and better defined.

Recent experimental and theoretical analyses of transport of sediment waves have indicated that in simple flumes or one-dimensional sediment transport models, dispersion of sediment should predominate over translation of waves (Lisle *et al.*, 1997). Flume and theoretical analysis has emphasized relatively large influxes of sediment, which cause substantial topographic changes to the channel long profile. In these models, the rate of change of the channel bed elevation is directly proportional to the curvature of the energy grade line as flow is deformed over the sediment wave. Under these conditions, and relatively large Froude numbers, sediment is transported from the peak of the wave and distributed downstream, thereby dispersing the wave. Lisle *et al.* (1997) found that with Froude numbers less than 0.2 some components of wave translation were evident. These authors summarized their results by stating that their analysis showed that changes in bed slope alone are insufficient to cause significant downstream translation of waves; that initial evolution of a sediment wave will be characterized by dispersion because of the effect of channel slope. They state, however, that after significant decay of the waveform, other influences may cause downstream translation of coherent sediment features.

We believe that the wave-like forms - vertical and horizontal - documented in the Ozarks result from a balance of dispersive and translational transport processes and from boundary conditions that favour accumulation of gravel in the channel network. Dispersion of individual waves undoubtedly occurs, but dispersion may be minimized in this system because transport occurs at relatively low Froude numbers, because abrasion of chert bed material is minimal, and because waves are broad, low-amplitude structures for which bed slope does not predominate in wave evolution. Translational components of wave transport in a drainage network can be accentuated by merging of waves in a channel network. In addition, dispersion of sediment waves may be counteracted in part by processes that reform waves, for example, valley-scale characteristics that allow sediment to accumulate and flush episodically from storage sites like disturbance reaches. This 'sticky valve' concept has been used to account for unpredictable riffle/pool spacings in Ozarks streams (McKenney, 1997). The balance of dispersive and translational processes may change with time and distance downstream. For example, small initial influxes of gravel - similar to the initial 'packets' postulated in the uniform routing model - would have little topographic relief and would therefore be minimally subject to dispersion. As 'packets' merge and accumulate into larger waveforms they may produce significant local increases in channel slope, and thereby enhance dispersion. Hence, dispersive processes may prevent the accumulation of large, translating waves as depicted in the uniform routing model at timesteps 24–35 (Figure 10).

Recognition of the wave-like accumulations of excess gravel in the bedload of rivers subjected to widespread, low-intensity disturbance has implications for concepts of sediment routing and for resource management. Whereas most of the effort in modelling sediment routing at the drainage-basin scale has been focused on fine sediment fractions and associated nutrients and contaminants, this study supports the idea that slower-moving bedload sediment can accumulate to substantial volumes. In addition to degrading stream habitat and decreasing channel capacity (Figure 11C), accumulations of bedload can cause channel instability that results in an increased rate of remobilization of fine sediment stored in floodplain deposits. Translation of a lagged wave of bedload through river reaches that previously have accumulated excess contaminant-laden fine sediment in floodplain deposits may accelerate redelivery of stored contaminants to the channel. Because gravel bedload is useful as construction aggregate, identification of sites of excess accumulation may indicate where gravel can be removed from the sediment transport system while minimizing adverse effects on the aquatic ecosystem.

#### ACKNOWLEDGEMENTS

This study was carried out with funding contributed by the US Geological Survey (USGS) Global Change Research Program, the Ozark National Scenic Riverways (National Park Service), and the Missouri Department of Conservation.

#### REFERENCES

- Albertson, P. E., Meinert, D. and Butler, G. 1995. Geomorphic investigation of Fort Leonard Wood, US Army Corps of Engineers, Waterway Experiment Station, Technical Report **GL-95-19**, 105 pp.
- Alexander, T. W. and Wilson, G. L. 1995. Technique for estimating the 2- to 500-year flood discharges on unregulated streams in rural Missouri, US Geological Survey Water-Resources Investigations Report **95-4231**, 33 pp.
- Arnold, J. G., Williams, J. R. and Maidment D. R. 1995. 'Continuous-time water and sediment-routing model for large basins', *Journal of Hydraulic Engineering*, **121**, 171–183.
- Batek, M. J. 1994. Presettlement vegetation of the Current River watershed in the Missouri Ozarks, unpublished MS thesis, University of Missouri, Columbia, 264 pp.
- Baver, L. D. 1935. Soil erosion in Missouri, University of Missouri College of Agriculture, Agricultural Experiment Station Bulletin **349**, 64 pp.
- Bobbitt, K. 1996. Drainage basin controls on gravel distribution in the Current River, Missouri, undergraduate thesis, Carleton College, Northfield, Minnesota, 65 pp.
- Church, M. 1983. 'Pattern of instability in a wandering gravel bed channel', International Association of Sedimentologists, Special Publication, **6**, 169–180.
- Costa, J. E. 1975. 'Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland', *Geological Society of America Bulletin*, **86**, 1281–1286.
- EOSAT 1992. Thematic mapper digital data, Path 24, row 34, Reston, Va.
- ESRI 1992. Dynamic segmentation—Modeling linear features, Environmental Systems Research Institute, Inc., Redlands, California, 72 pp.
- Gilbert, G. K. 1917. Hydraulic-mining debris in the Sierra Nevada, US Geological Survey Professional Paper **105**, 154 pp.
- Guyette, R. P. and McGinnes, E. A. 1982. 'Fire history of an Ozark glade in Missouri', *Transactions of the Missouri Academy of Sciences*, **16**, 85–93.
- Hall, L. 1958. Stars Upstream—Life along an Ozark river, University of Missouri Press, Columbia, 262 pp.
- Happ, S. C. 1945. 'Sedimentation in South Carolina Piedmont valleys', *American Journal of Science*, **243**, 113–126.
- Hassan, M. A., Church, M. and Schick, S. P. 1991. 'Distance of movement of coarse particles in gravel bed streams', *Water Resources Research*, **27**, 503–511.
- Hauck, H. S., Huber, L. G. and Nagel, C. D. 1996. Water resources data, Missouri—water year 1995, US Geological Survey Water-Data Report **MO-95-1**, 320 pp.
- Hooke, R. LeB. 1994. 'On the efficacy of humans as geomorphic agents', *GSA Today*, **4**(217), 224–225.
- Jacobson, R. B. 1995. 'Spatial controls on patterns of land-use induced stream disturbance at the drainage-basin scale—An example from gravel-bed streams of the Ozark Plateaus, Missouri', in Costa, J. E., Miller, A. J., Potter, K. W. and Wilcock, P. R. (Eds), *The Wolman Volume, Geophysical Monograph 89*, American Geophysical Union, 219–239.
- Jacobson, R. B. and Coleman, D. J. 1986. 'Stratigraphy and recent evolution of Maryland Piedmont flood plains', *American Journal of Science*, **286**, 617–637.
- Jacobson, R. B. and Primm, A. T. 1997. Historical land-use changes and potential effects on stream disturbance in the Ozark Plateaus, Missouri, US Geological Survey Water-Supply Paper **2484**, 85 pp.
- Jacobson, R. B. and Pugh, A. L. 1992. 'Effects of land use and climate shifts on channel instability, Ozark Plateaus, Missouri, U.S.A.', Proceedings of the Workshop on the Effects of Global Climate Change on Hydrology and Water Resources at the Catchment Scale, Japan—US Committee on Hydrology, Water Resources and Global Climate Change, Public Works Research Inst., Tsukuba City, 423–444.

- Jacobson, R. B. and Pugh, A. L. (1997). Riparian vegetation controls on the spatial pattern of stream-channel instability, Little Piney Creek, Missouri, US Geological Survey Water-Supply Paper **2494**.
- James, L. A. 1993. 'Sustained reworking of hydraulic mining sediment in California—G. K. Gilbert's sediment wave model reconsidered', *Zeitschrift für Geomorphologie*, **88**, 49–66.
- James, L. A. 1997. 'Channel incision on the lower American River, California, from streamflow gage records', *Water Resources Research*, **33**, 485–490.
- Knox, J. C. 1977. 'Human impacts on Wisconsin stream channels', *Association of American Geographers Annals*, **67**, 323–342.
- Krusekopf, H. H., DeYoung, W., Watkins, W. I. and Deardorff, C. E. 1918. 'Soil survey of Reynolds County, Missouri', Field Operations of the Bureau of Soils, 1918, US Bureau of Soils, 1307–1331.
- Ladd, D. 1991. 'Reexamination of the role of fire in Missouri oak woodlands', Proceedings of the Oak Woods Management Workshop, Eastern Illinois University, Charleston, 67–80.
- Leopold, L. B., Wolman, M. G. and Miller, J. P. 1964. Fluvial processes in Geomorphology, W. H. Freeman, San Francisco, 522 pp.
- Lisle, T. E., Pizzuto, J. E., Ikeda, H., Iseya, F. and Kodama, Y. 1997. 'Evolution of a sediment wave in an experimental channel', *Water Resources Research*, **33**, 1971–1981.
- Love, K. 1990. 'Paradise lost', *Missouri Conservationist*, **51**, 31–35.
- McKenney, R. 1997. Formation and maintenance of hydraulic habitat units in streams of the Ozark Plateaus, Missouri and Arkansas, unpublished PhD dissertation, Pennsylvania State University, 347 pp.
- McKenney, R. and Jacobson, R. B. 1996. Erosion and deposition at the riffle–pool scale in gravel-bed streams of the Ozark Plateaus, Missouri and Arkansas US Geological Survey Open-File Report **96-655A**, 171 pp.
- Madej, M. A. 1995. Recent changes in channel-stored sediment, Redwood Creek, Northwestern California, 1947 to 1980, US Geological Survey Professional Paper **1454-O**, 27 pp.
- Magilligan, F. J. 1985. 'Historical floodplain sedimentation in the Galena River basin, Wisconsin and Illinois', *Association of American Geographers Annals*, **75**, 583–594.
- Mann, M. E. and Lees, J. 1996. 'Robust estimation of background noise and signal detection in climatic time series', *Climatic Change*, **33**, 409–445.
- Meade, R. H. 1985. 'Wavelike movement of bedload sediment, East Fork River, Wyoming', *Environmental Geology and Water Science*, **7**, 215–225.
- Meade, R. H., Yuzyk, T. R. and Day, T. J. 1990. 'Movement and storage of sediment in rivers of the United States and Canada', in Wolman, M. G. and Riggs, H. C. (Eds), Surface Water Hydrology, *The Geology of North America*, O-1, Geological Society of America, Boulder, Colorado, 255–280.
- Missouri Division of Geology and Land Survey 1979. Geologic map of Missouri, scale 1:500 000 Missouri Department of Natural Resources, Rolla, Missouri.
- Nakamura, F., Maita, H. and Araya, T. 1995. 'Sediment routing analyses based on chronological changes in hillslope and riverbed morphologies', *Earth Surface Processes and Landforms*, **20**, 333–346.
- Rafferty, M. D. 1980. The Ozarks Land and Life, University of Oklahoma Press, Norman, 282 pp.
- Roehl, J. W. 1962. 'Sediment source areas, delivery ratios, and influencing morphological factors', International Association of Scientific Hydrology, Publication **59**, 202–213.
- Saucier, R. T. 1983. 'Historic changes in Current River meander regime', Proceedings of the Conference, Rivers '83, American Society of Civil Engineers, 180–190.
- Simon, A. and Thorne, C. R. 1996. 'Channel adjustment of an unstable coarse-grained stream—Opposing trends of boundary and critical shear stress, and the applicability of extremal hypotheses', *Earth Surface Processes and Landforms*, **21**, 155–180.
- Stevens, D. L. 1991. A Homeland and a Hinterland—The Current and Jacks Fork Riverways, National Park Service, Omaha, Nebraska, 248 pp.
- Trimble, S. W. 1974. Man-induced soil erosion on the southern Piedmont, 1700–1970, Soil Conservation Society of America, Ankeny, Iowa, 180 pp.
- US Bureau of the Census 1850–1996. Census of the United States, US Department of Commerce.
- US Environmental Protection Agency 1994. EPA Reach File Version 3.0 Alpha Release (RF -Alpha) Technical Reference, US Environmental Protection Agency, Office of Water, Washington, D.C., 23 pp.
- US Geological Survey 1990. Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps, National Mapping Program Technical Instructions, Data Users Guide 4, 33 pp.
- Vineyard, J. D. and Feder, G. L. 1974. Springs of Missouri, Missouri Division of Geology and Land Survey, Water Resources Report **29**, 266 pp.
- Walling, D. E. 1988. 'Erosion and sediment yield research – some recent perspectives', *Journal of Hydrology*, **100**, 113–141.
- Wathen, S. J. and Hoey, T. B. 1998. 'Morphological controls on the downstream passage of a sediment wave in a gravel-bed stream', *Earth Surface Processes and Landforms*, **23**, 715–730.
- Wolman, M. G. 1967. 'A cycle of sedimentation and erosion in urban river channels', *Geografiska Annaler*, **49A**, 385–395.
- Wolman, H. G. 1977. 'Changing needs and opportunities in the sediment field', *Water Resources Research*, **13**, 50–54.